Waddington, I., Thomas, P., Taylor, R., & Vaughan, G. J. (2017). J-value assessment of remediation measures following the Chernobyl and Fukushima Daiichi nuclear power plant accidents. *Process Safety and Environmental Protection*, *112 Part A*, 63–76. https://doi.org/10.1016/j.psep.2017.07.003

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Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

J-value assessment of remediation measures following the Chernobyl and Fukushima Daiichi nuclear power plant accidents

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ARTICLE INFO

Article history:
Received 28 April 2016
Received in revised form 3 June 2017
Accepted 3 July 2017

Keywords:
Risk management
J-value
Disaster recovery
Chernobyl
Fukushima Daiichi
Nuclear remediation

ABSTRACT

Actions set in train shortly after the accidents at Chernobyl (1986), and Fukushima Daiichi (2011) had the aim of reducing the more immediate health effects on people living near the plants, with population relocation being especially prominent. The important topic of relocation is the subject of a companion paper, and this article will concentrate on other measures, such as soil treatment and urban decontamination, that have been put in place to reduce the radiation risks in the medium and long term to people living and farming in areas subject to some degree of radioactive contamination. The J-value method of risk assessment has been used to judge the cost-effectiveness of a range of agricultural and urban remediation actions. Many remedial measures instituted after the Chernobyl and Fukushima Daiichi accidents have been found to be highly cost-effective.

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1. Introduction

The paper uses the J-value (Thomas et al., 2006a, 2010) to analyse a range of remediation measures that were applied following the big nuclear power plant accidents at Chernobyl in 1986 and Fukushima Daiichi in 2011. The Judgement- or J-value balances the cost of the action against the safety benefit so as to preserve the notional quality of life of those affected, as defined by the life quality index introduced by Nathwani and Lind (1997). See also Nathwani et al. (2009). The J-value is the ratio of the amount spent or being contemplated to the maximum that can be spent without reducing the life quality of those involved. Hence a J-value up to 1.0 represents justifiable spending, but a J-value of more than 1.0 indicates that the action is not cost effective as the notional life quality of those affected will be reduced. Further discussion of the philosophy leading to the J-value is given in Section 2 of Waddington et al. (2017a).

On 26 April 1986, an accident at the nuclear power plant at Chernobyl in the Ukraine resulted in a catastrophic failure of the core containment. A fire in the exposed graphite core burned for ten days before being brought under control. The accident released into the atmosphere large amounts of isotopes of relatively short half-life (such as iodine-131 with a half-life of 8 days), together with much lower quantities, in terms of activity, of long-lived isotopes such as strontium and caesium (half-lives of about 30 years) and plutonium (half-life about 24,000 years). The pattern of radionuclide deposition reflected wind direction and rainfall as they varied over the ten days or so of the main release, with a total area of 150,000 km^2 in Ukraine, Belarus and Russia eventually being classified as 'contaminated' (UNSCEAR, 2008, p50). Land designated in this way had a surface contamination above 37 $kBq\,m^{-2}$, giving an annual individual effective dose of approximately 1 $mSv\,y^{-1}$ to people living there.

Several publications provide helpful insights into the development of countermeasures and the criteria underpinning them. Konstantinov

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http://dx.doi.org/10.1016/j.psep.2017.07.003
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(1992), for example, details the evolution of responses during the various phases following the accident, from the early actions to the later remedial measures when, in theory, greater consideration might be given to cost effectiveness. However what was possible later could be constrained by earlier decisions made in deference to immediate public concerns. Konstantinov provides a chronology of the increasing scale of protective measures and how the criteria changed in the five years following the accident. He highlights the strong effect that socio-political factors had on decision making in the intermediate and later recovery phases at Chernobyl.

Avetisov (1992) draws attention both to the stringency of temporary permissible levels in the USSR following Chernobyl and also to the wide variations in the numbers adopted in different countries, with further discussion and detail being given in Vargo (2000). IAEA (2001) discusses the effects of the accident over time on day to day living in the contaminated regions as well as its impact on flora and fauna, with remedial actions listed for the Ukraine, Belarus and Russia. Smith and Beresford (2005) provide a readable, scientific account of the environmental effects of the radioactive fall-out from the Chernobyl accident.

A quarter of a century later the Great East Japan Earthquake of 11 March 2011 triggered a series of tsunamis that hit the east coast of Japan and overwhelmed the Fukushima Daiichi nuclear power plant. Following destruction of the main and back-up power supplies, the cooling systems failed which resulted in damage to the reactor cores and vessels. Operations to reduce pressure in the reactor vessels and, possibly, leaks from the vessels, led to the release of radionuclides into the reactor buildings. The over-heated fuel assemblies caused a chemical reaction that produced hydrogen gas in the reactor buildings which subsequently ignited and exploded, releasing radionuclides into the environment (UNSCEAR, 2013, p34).

Actions were taken in the immediate aftermath of these accidents, particularly the relocation of people (see Waddington et al., 2017a), with the intention of reducing the health effects on those living near the nuclear power plants. Food restrictions were imposed following the Chernobyl accident even in distant countries such as the UK, where Waddington et al. (2017b) have examined the justification for finally lifting the ban on the consumption of meat from sheep reared in some upland areas in England, Scotland and Wales 2½ decades after the event.

This paper concentrates on evaluating the effectiveness of remedial actions applied in the agricultural sector in the vicinity of Chernobyl and also to the urban environments around both Chernobyl and Fukushima Daiichi. Some of these countermeasures were put into force within a year of the accident happening, but we have considered others that were being considered for implementation in affected areas more than 20 years after the Chernobyl accident.

The paper applies the Judgement- or J-value, outlined in Section 2, to assess remedial measures after these two major nuclear accidents. Section 3 discusses the cost effectiveness of ongoing agricultural remediation measures in rural communities still affected by the Chernobyl accident in 2010. Section 4 focuses on urban decontamination measures applied to towns and cities in Belarus and Ukraine in 1989 and Japan in 2012. A concluding section considers what has been learnt about the cost-effectiveness of post-accident remediation actions.

Obviously the paper will cover only a limited number of the remedial actions applied after the Chernobyl and Fukushima Daiichi accidents but the method would be able handle any other countermeasure, given the availability of basic data on dose averted and cost. The remediation measures we have considered here were applied in inhabited areas but the same J-value technique could also be used in cases where remediation precedes the return of evacuated people.

2. The J-value

The J-value framework provides an objective tool to assess the cost-effectiveness of safety schemes that reduce the risk to human life (Thomas et al., 2006a). Based on established economic theory, the J-value allows safety expenditure to be balanced against the extension of life-expectancy brought about by the scheme. It is postulated that the fundamental factors influencing the quality of life for an individual are how long he or she can expect to live from now on (life expectancy, X_d) and how much he/she will have available to spend (income, G). The life quality index, Q, can then be defined by

$$Q = G^q X_d \tag{1}$$

The subscript 'd' on life expectancy, X, allows for the generality of discounting of future utility of income, where the discount factor can be incorporated equivalently into the 'discounted' life expectancy (Thomas et al., 2006a, 2010). Meanwhile the parameter, q, is the complement of risk-aversion, $\varepsilon = 1 - q$. Thomas and Waddington (2017) used pan-national data to derive a common value of risk-aversion, $\varepsilon = 0.95$, applicable to most countries in the world. The figure reduces to 0.91 in the case of highly developed countries such as the USA and the UK. Hence $\varepsilon = 0.95$ was used in the characterisation of the USSR and the Former Soviet Union, while $\varepsilon = 0.91$ was adopted for Japan.

Risk-aversion is a mathematically defined, dimensionless parameter that characterises the individual's feeling of unease in the presence of uncertainty. Aversion to risk may occur in a multiplicity of contexts: when considering dangers to health, to life style, to status, and so on, as well as to wealth, where it is regarded a bedrock concept by the insurance industry. But see Thomas (2013) for an example unrelated to money: here the apparently anomalous behaviour of 5-year old children at play is explained quantitatively using risk-aversion.

The value of risk-aversion adopted when considering decisions on life extension (what might be termed loosely "life or death" decisions) has been shown to be constant and common to a large swathe of humanity (Thomas and Waddington, 2017; Thomas, 2017). However an individual's risk-aversion is not generally a fixed figure, but will increase with the magnitude of his or her potential loss. Thomas (2016) provides a full introduction to and discussion of the topic.

An average individual may maintain or improve his or her life quality by giving up part of his/her annual income, δG, to pay for a protection system that restores his/her life expectancy to what it would be in the absence of the risk (e.g. Thomas et al., 2006a, Eq. (14)):

$$\delta G \le \frac{G}{q}\frac{\delta X_d}{X_d} \tag{2}$$

where δX_d is the loss of discounted life expectancy if exposed to the risk. A population of N affected individuals should be willing to spend, per year, up to

$$\delta G_N = N\,\delta G = \frac{GN}{q}\frac{\delta X_d}{X_d} \tag{3}$$

If an annual amount $\delta\hat{G}_N$ is actually spent on the protection scheme to protect the N individuals, then the J-value is defined by

$$J = \frac{\delta\hat{G}_N}{\delta G_N} \tag{4}$$

3. Additional remediation at Chernobyl 20 years after the accident

3.1. *Introduction*

Remedial measures following a release of radioactivity might involve:

- treating the soil
- removing the soil
- providing animal feeds produced away from the contaminated area so as to minimise uptake of radioactivity into the human food chain
- removal of vegetation,
- washing down of hard surfaces, and
- information campaigns.

The range of agricultural countermeasures employed and their effectiveness in reducing the total radiation dose of the population at Chernobyl has been summarised in detail by Alexakhin (1993), Fesenko et al. (2007) and Jacob et al. (2001). The issue of how best to use scarce resources has been an area of particular interest.

Jacob et al. (2009) investigated the cost-effectiveness of additional remediation strategies to be implemented in 2010 to reduce the radiation exposure of rural communities still experiencing residual effects from the 1986 Chernobyl accident. Their study considered settlements having fewer than 10,000 inhabitants where the average dose received by those in the upper 10% of the dose distribution ("reference persons") was estimated to have been 1 mSv or above in 2004. Jacob et al. calculated the doses in settlements using a software tool, ReSCA (Remediation Strategies after the Chernobyl Accident), and identified 290 communities as meeting the criteria. The total population of these communities was 78,172, with an average of 270 people per settlement.

It should be borne in mind that an imposed dose of 1 mSv per year (and falling) for the worst affected 10% of the inhabitants of a settlement is already at a very low level: it is a tenth of the dose "below which intervention is not likely to be justifiable" (ICRP, 1999), and exposure to such a dose over a period of 50 years can be calculated to cut life expectancy by about 2 weeks based on International Committee on Radiation Protection (ICRP) coefficients[1] (Thomas and Jones, 2009). Nevertheless Jacob et al. were able to recommend additional remediation measures to be implemented in 2010 as "quite cost-effective". This paper will apply the J-value to check the validity of this recommendation.

Six specific remedial actions were considered in the Jacob study of 2009:

1. Radical Improvement of grassland (RI)—removing vegetation, ploughing, liming, fertilization and reseeding.
2. Ferrocyn Application to cattle (FA)—an additive to cattle feed that reduces caesium uptake and transfer to milk and meat.
3. Feeding Pigs with uncontaminated fodder (FP)—for two months before slaughter.
4. Mineral Fertilizers applied to potato fields (MF)—reducing root uptake of caesium by increasing the potassium to caesium ratio in the soil through the application of potassium-rich fertilisers.
5. Information campaign on Mushrooms and other forest produce (IM)—common components of the diet in the region, but subject to high levels of contamination.
6. Replacement of contaminated Soil (RS)—from around the houses in the most contaminated areas.

While an area used for agricultural production might benefit from one of the first 5 remediation measures in this list, the potential benefit from the last, RS, will apply only to residential housing.

3.2. *The method used in the Jacob study*

The intention of the Jacob study (Jacob et al., 2009) was to rank in priority order the pairings of countermeasure and the location to which it was applied. An overview of the method is presented here, with a more detailed explanation given in Appendix A.

The Jacob study examined Strategies 1 and 2. Strategy 2, which seeks to maximise the averted dose for any given remediation budget, will be introduced first as it is the more basic.

3.2.1. *Strategy 2*

The location, which may be an agricultural production area or a residential neighbourhood containing a cohort of 10 people, is given the identifier, k. The remedial action, r, will be one of {RA, FA, FP, MF, IM, RS}.

For the case where the ranking is based purely on cost per unit radiation dose averted, the Jacob algorithm seeks to find the remedial action, r, and the location, k, that maximise the objective function:

$$\frac{\min_{k,r} C_{Dkr}}{C_{Dkr}} \quad \text{over all } k \text{ and } r \tag{A.3}$$

where C_{Dkr} is the cost of averting a man-Sievert (€ Sv^{-1}) at location k under remedial action, r. (It is understood that each location is to be served by only one remediation measure, as discussed in Appendix A.)

Once the most cost-effective pairing of location and remedial action, $(k = k_1, r = r_1)$, has been found, location k_1 may be removed from consideration and the process repeated for the remaining $(n_k - 1)$ locations. This process is continued until there are no more locations left, producing a priority ordering, $(k_1, r_1), (k_2, r_2), (k_3, r_3), \ldots, \left(k_{n_k}, r_{n_k}\right)$.

Fig. 1a–d provides an illustration of the first four steps in the algorithm when there are 10 locations and 6 possible remedial actions with representative costs. At each stage the most cost-effective pairing of remedial action and location will cause the objective function to be equal to unity, while any other pairing will be less than 1.0. Thus the most cost-effective pairing is (5, FA), and this is followed by (7, RS), with (3, FA) next and then (4, FA).

Jacob et al. (2009) assume a fixed budget for remediation in each republic, so that the remedial actions should then be undertaken in the sequential order of priority until all the money has been used up. They call the resulting remedial spending decisions "Strategy 2".

[1] Although studies of the survivors of the Hiroshima and Nagasaki bombings make a major contribution to our knowledge of the effects of nuclear radiation on people, the ICRP coefficients are intended to characterise in a conservative way the dose responses of people from all nations in the world.

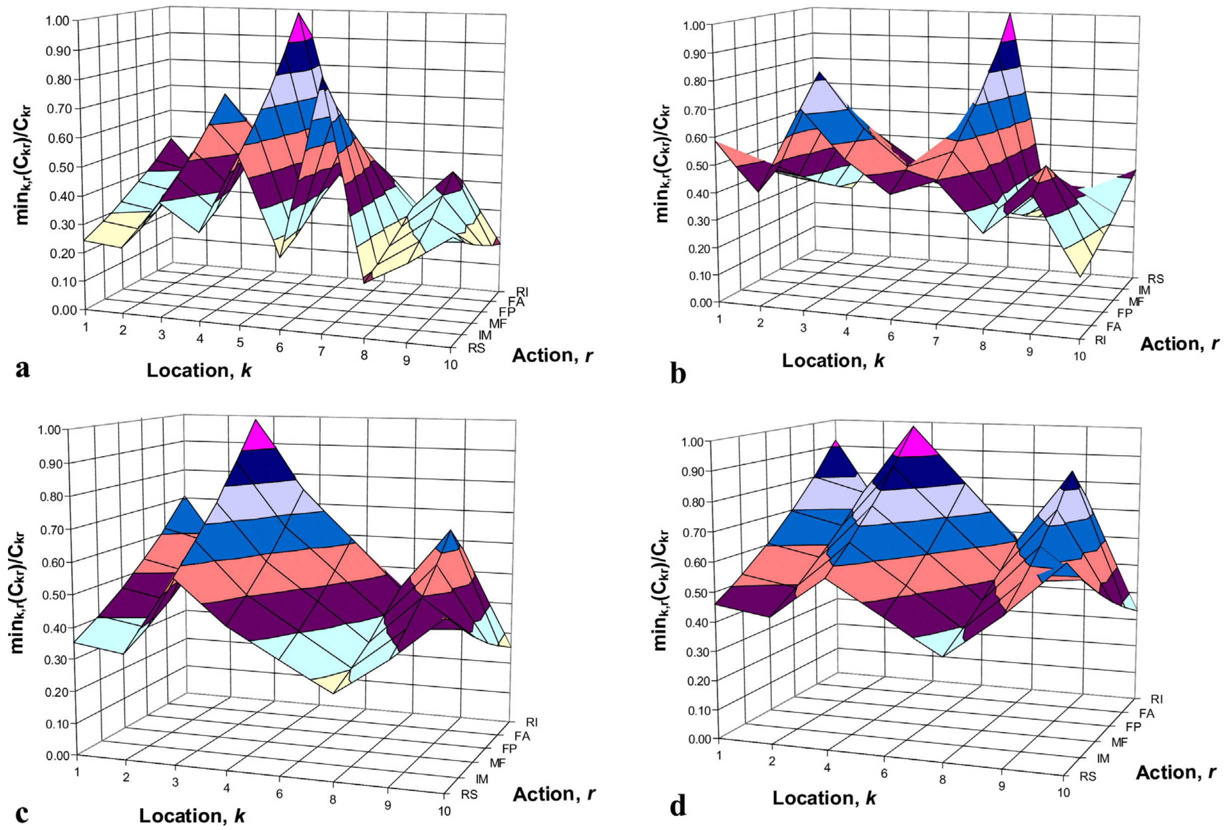

Fig. 1 – Applying objective function (A.3) to 6 remedial actions and 10 locations. (a) The most cost-effective dose reduction occurs when remedial action, FA, is applied to location 5. (b) Location 5 is eliminated and the 2nd most cost-effective dose reduction occurs when remedial action, RS, is applied to location 7. (c) Locations 5 and 7 have been eliminated so that the 3rd most cost-effective dose reduction is achieved by applying remedial action, FA, to location 3. (d) Locations 5, 7 and 3 have been eliminated so that the 4th most cost-effective dose reduction comes when remedial action, FA, is applied to location 4.

For Strategy 2, Jacob et al. considered possible remediation budgets for each republic of €0.5M, €1M and €2M, picking out for special attention the following budgets:

- €1M for Belarus
- €2M for the Russian Federation
- €0.4M for Ukraine. This sum was lower than for the other two republics because the reference person's dose in every Ukrainian settlement was found be reduced below 1 mSv y^{-1} when this amount was spent under Strategy 2.

These budgets are described in the Jacob study as "arbitrarily chosen funds". See Table 5 of Jacob et al. (2009).

There is only one possible remediation measure for each 10-person, residential cohort, namely removal of soil, RS. This remedial action competes with the other remediation measures considered for Strategy 2 on how many man-Sieverts of radiation dose can be averted for each Euro spent.

3.2.2. *Strategy 1*

The authors now introduce a further, subjective parameter, the degree-of-acceptability, D_A, with the words being hyphenated in this paper to indicate that a special meaning has been reserved to the term. Jacob et al. found the degree-of-acceptability for a remedial action to be independent of both country and settlement, and Table 1 lists the numerical value, D_{Ar}, for the six remedial actions.

A new objective function emerges as:

$$\beta \frac{\min_{k,r} C_{Dkr}}{C_{Dkr}} + (1-\beta) D_{Ar} \text{ over all } k \text{ and } r \tag{A.6}$$

where D_{Ar} is the degree-of-acceptability for remediation action, r, and β is a weighting parameter set by the user: $0 \le \beta \le 1$. The values of r and k are now adjusted so as to maximise objective function, (A.6). A priority ordering of (r_i, k_i) is now generated for Strategy 1 in a similar way as was done for Strategy 2.

The size of subjective weighting factor, β, is clearly of high importance. $\beta = 1$ means that objective function (A.6) becomes identical to objective function (A.3), implying that remedial actions will be judged purely on their effectiveness in reducing radiation dose, as measured by the cost per unit dose reduction.

On the other hand, $\beta = 0$ means that the degree-of-acceptability will be the sole criterion for adoption, since objective function (A.6) is now simply D_{Ar}. Problems arise with such an objective function, since the cost of averting unit radiation dose becomes irrelevant. The lack of a link between the degree-of-acceptability and location, k, is now reflected in an identical lack of connection between objective function (A.6) and location, k, when $\beta = 0$. In such a case, either RI or MF would always be the selected options for all agricultural locations, irrespective of location-dependent cost effectiveness. Furthermore, because the degree-of-acceptability takes its lowest value, $D_{A,RS} = 0.1$, for $r = RS$ (see Table 1), all the resi-

Table 1 – Degree-of-acceptability for the 6 remedial actions.

Index no.	Remedial action, r	Two-letter acronym	Degree-of-acceptability, D_{Ar}
1	Radical improvement	RI	1.0
2	Ferrocyn application to cows	FA	0.75
3	Clean feed to pigs	FP	0.6
4	Mineral fertiliser for potatoes	MF	1.0
5	Information on mushrooms	IM	0.5
6	Replacement of contaminated soil	RS	0.1

Table 2 – J-value analysis of agricultural remediation strategies for the three republics. Strategy 2 is based on cost per dose averted. Strategy 1 includes degree-of-acceptability.

	Costs (1000 Euro)	Population affected	Averted dose (manSv)	δX (hours)	J-value
Strategy 2					
Belarus	1002	9615	27.3	23.9	0.73
Russia	2001	57,960	110.9	15.5	0.18
Ukraine	378	10,597	23.5	18.5	0.25
All	3381	78,172	161.7	16.9	0.21
	Costs (1000 Euro)	**Population affected**	**Averted dose (manSv)**	**δX (hours)**	**Apparent J-value**
Strategy 1					
Belarus	1003	9615	21.4	18.8	0.93
Russia	2024	57,960	75.6	10.6	0.27
Ukraine	1372	10,597	45.3	35.6	0.47
All	4399	78,172	142.3	15	0.32

dential cohorts notionally implementing RS would always be placed equal last in the priority ordering.

Jacob et al. avoid the problems just described when $\beta = 0$ by choosing to set $\beta = 0.1$. thus allowing the cost per unit dose reduction to have some influence while retaining a large weighting for the degree-of-acceptability parameter.

When the budget for remediation is fixed, the remedial actions will be undertaken in the sequential order of priority until all the money has been used up. Jacob et al. denote by "Strategy 1" the strategic choices for remedial spending generated when $\beta = 0.1$.

Jacob et al. suggested budgets for each republic under Strategy 1 ("arbitrarily chosen funds") in the following amounts:

1. €1M for Belarus
2. €2M for the Russian Federation
3. €0.4M + €1.0M = €1.4M for Ukraine,

The budgets for Belarus and the Russian Federation are the same as for Strategy 2. However,

the budget for the Ukraine has been increased by a million Euros over the amount, €0.4M, assigned to that republic under Strategy 2. This brings the budget for the Ukraine more in line with those of Belarus and Russia.

3.3. *Performing J-value analyses for Ukraine, Belarus and the Russian Federation*

Table 5 of Jacob et al. includes the aggregate costs of implementing Strategies 1 and 2 across each of the republics, Ukraine, Belarus and Russia, together with overall costs per unit averted dose. We summarize the costs and averted doses for these remedial actions in Table 2 below, which allow J-values to be calculated for each Strategy as applied in the three republics. (Any doses received by the remediation workers could be incorporated into the J-value analysis, but we did not find data on these.)

Meanwhile the Supplementary Tables of Jacob et al. identify, for each republic, the 15 settlements that delivered the highest cost-effectiveness as a result of adopting their best remedial measure under each of Strategy 2 and Strategy 1. Averted doses and costs are given in each case, allowing J-values to be calculated for 15 specific components within each republic under each Strategy. See Tables 3–8 below.

Clearly Strategy 1 depends strongly on degree-of-acceptability, D_{Ar}, which characterises the additional benefit derived from the remedial action over and above reducing radiation dose:

> "Side effects of remedial actions, as, e.g., the increase of potato yield by applying mineral fertilizers, have been considered in ReSCA by defining a degree of acceptability of the remedial actions."

The customary implication that side effects are unwanted does not apply here: these additional effects are desirable.

Fesenko et al. (2013) clarify that the degree-of-acceptability is a subjective measure:

> "Side effects of the remedial actions are subjectively quantified by a 'degree of acceptability'."

In so far as the additional concerns behind the choices making up Strategy 1 may have been social or political, their early admixture would part company from the sequential approach that we would recommend with the J-value. If the "balance sheet" methodology is used (Taylor et al., 2003), each element of the decision making process is developed separately until the final synthesis. Such a procedure is needed in order to maintain transparency, in conformance with the recommendations of the World Health Organisation's Chernobyl Forum Expert Group on Health (2006). The application of the J-value allows a baseline to be established, after which additional factors, such as public opinion, may then be included in the balance sheet before the final decision is taken. But their inclusion needs to be transparent.

Table 3 – The top fifteen remedial actions for Belarusian settlements in 2010, for Strategy 2 (derived from Table S5a of Jacob et al.). δX gives the increase in life expectancy for a settlement with the average population of 270.

Settlement (area number[a])	Remedial action	Costs (k€)	Averted dose (manSv)	δX (hours)	J-value
Koshara (53)	FA	0.9	0.095	3.2	0.2
Dobraya Volya (52)	FA	0.2	0.031	1	0.14
Borovaya (56)	FA	0.1	0.017	0.6	0.12
Slovechno (12)	FA	0.8	0.101	3.4	0.17
Zarakitnoe (66)	FA	0.1	0.015	0.5	0.14
Konotop (17)	FA	0.4	0.049	1.6	0.17
Luben’ (68)	FA	0.1	0.007	0.2	0.31
Tul’govichi (71)	FA	0.1	0.013	0.4	0.16
Svetilovichi (4)	FA	2.1	0.221	7.4	0.2
Grushevka (16)	FA	0.9	0.093	3.1	0.2
Budishe (49)	FA	0.2	0.021	0.7	0.2
Krasny Bereg (24)	FA	0.6	0.056	1.9	0.23
Kosel’ (40)	FA	0.3	0.023	0.8	0.28
Svetilovichi (4)	RS	3.3	0.268	10.6	0.22
Kholoch’e (73)	FA	0.1	0.006	0.2	0.34

[a] This is a reference to the geographical area covered by the settlement.

Table 4 – The top fifteen remedial actions for Russian settlements in 2010, for Strategy 2 (derived from Table S5b of Jacob et al.). δX gives the increase in life expectancy for a settlement with the average population of 270.

Settlement (area number)	Remedial action	Costs (k€)	Averted dose (manSv)	δX (hours)	J-value
Dobrodeevka (309–311)	FA	2.6	0.83	26.9	0.03
Zaborye (part)	RS	3.3	0.715	19.3	0.06
Unecha (331–333)	FA	1.1	0.25	8.1	0.05
Smyalch (21–27)	FA	5.7	0.95	30.6	0.06
Dobrodeevka (309–311)	RI	17.2	2.822	35.3	0.16
Guta Koretskaya (370–371)	FA	2.9	0.438	14.2	0.07
Novonovitskaya (59–62)	FA	1.6	0.245	8	0.07
Krasnaya Krynitsa (483)	FA	0.1	0.009	0.3	0.12
Yalovka	RS	3.3	0.485	12.9	0.09
Popovka (51–54)	FA	2.4	0.354	11.5	0.07
Zaborye	RS	3.3	0.476	12.5	0.09
Gannovka (456)	FA	0.1	0.017	0.5	0.06
Gordeevka (63–68)	FA	15.7	2.237	73.4	0.07
Trostan’ (63)	FA	0.5	0.068	2.2	0.08
Bezbozhnik (76–79)	FA	0.2	0.032	1.1	0.06

Table 5 – The top fifteen remedial actions for Ukrainian settlements in 2010, for Strategy 2 (derived from Table S5c of Jacob et al.). δX gives the increase in life expectancy for a settlement with the average population of 270.

Settlement (area number)	Remedial action	Costs (k€)	Averted dose (manSv)	δX (hours)	J-value
Vezhitsa (108)	FA	2	0.566	18.7	0.06
Vezhitsa (106)	FA	5.4	1.413	47.5	0.06
Elnoe (79)	FA	7.6	1.752	58.3	0.07
Vezhitsa (105)	FA	4	0.857	30.2	0.07
Rudnya-Karpilovskaya (130)	FA	1.2	0.24	8	0.08
Staroe Selo (94)	FA	1.4	0.276	11	0.08
Drozdyn (102)	FA	12	2.339	77.9	0.09
Lisichin (76)	FA	1	0.193	6.4	0.09
Staroe Selo (96)	FA	1.1	0.203	7.3	0.09
Drozdyn (101)	FA	9.2	1.661	57.4	0.09
Staroe Selo (100)	FA	6.8	1.152	40.4	0.09
Velikiy Cheremel (32)	FA	0.4	0.067	2.2	0.1
Staroe Selo (90)	FA	5.4	0.876	33	0.09
Rudnya Karpilovskaya (131)	FA	0.6	0.095	3.1	0.11
Vezhitsa (107)	FA	6	0.924	30.2	0.11

It is however, clear that economic considerations are the predominant reason for moving from the choices made under Strategy 2 to those represented by Strategy 1. While some of the agricultural countermeasures might have no function beyond radiation protection, others will carry additional monetary benefits. For example, adding Ferrocyn to the feed of cows (FA) will reduce radioactivity in milk and meat but make no difference to the quantity of milk or meat produced. Similarly, feeding pigs with uncontaminated fodder (FP) would bring no extra financial benefit beyond possibly offsetting fodder costs if the uncontaminated fodder were given free. However, the application of mineral fertilisers to potato fields (MF) can be expected to increase the size of the potato crop. Similarly, radical improvement of grassland (RI) will increase

Table 6 – The top fifteen remedial actions for Belarusian settlements in 2010, for Strategy 1 (derived from Table S4a of Jacob et al.). δX gives the increase in life expectancy for a settlement with the average population of 270.

Settlement (area number)	Remedial action	Costs (k€)	Averted dose (manSv)	δX (hours)	J-value
Borovaya (56)	RI	1.1	0.073	2.3	0.34
Koshara (53)	RI	10.5	0.467	14.9	0.49
Zarakitnoe (66)	RI	1.4	0.061	2	0.5
Luben’ (68)	RI	0.7	0.028	0.9	0.54
Tul’govichi (71)	RI	1.4	0.053	1.7	0.58
Svetilovichi (4)	RI	24.5	0.908	28.6	0.6
Grushevka (16)	RI	10.5	0.379	12.1	0.61
Budishe (49)	RI	2.5	0.084	2.7	0.64
Kosel’ (40)	RI	3.2	0.093	3.1	0.74
Novilovka	MF	0.1	0.003	0.1	0.7
Dobraya Volya (52)	RI	5.4	0.151	4.9	0.78
Konotop (17)	RI	8	0.213	6.8	0.82
Slovechno (12)	RI	18.5	0.465	15.1	0.86
Selishe-2 (39)	RI	1.8	0.044	1.4	0.9
Kholoch’e (73)	RI	1.1	0.026	0.8	0.97

Table 7 – The top fifteen remedial actions for Russian settlements in 2010, for Strategy 1 (derived from Table S4b of Jacob et al.). δX gives the increase in life expectancy for a settlement with the average population of 270.

Settlement (area number)	Remedial action	Costs (k€)	Averted dose (manSv)	δX (hours)	J-value
Dobrodeevka (209–311)	RI	17.2	3.374	104	0.06
Unecha (331–333)	RI	7.4	1	31	0.08
Krasnaya Krynitsa (483)	RI	0.4	0.042	1.3	0.1
Smyalch (21–27)	RI	37	3.851	119	0.1
Gannovka (456)	RI	0.8	0.081	2.5	0.11
Trostan’ (63)	RI	3.1	0.318	9.8	0.11
Bezbozhnik (76–79)	RI	1.6	0.152	4.7	0.12
Novonovitskaya (59–62)	RI	10.5	1.014	31	0.11
Gordeevka (63–68)	RI	101.8	9.783	300	0.11
Zaitsev (73–75)	RI	1.2	0.111	3.4	0.12
Guta Koretskaya (370–371)	RI	18.7	1.756	54.1	0.12
Zamishevo (510)	RI	14.8	1.378	42.7	0.12
Velichka (523)	RI	0.4	0.036	1.1	0.12
Popovka (51–54)	RI	15.6	1.439	44.2	0.12
Griva (209–210)	RI	0.8	0.066	2.1	0.13

Table 8 – The top fifteen remedial actions for Ukrainian settlements in 2010, for Strategy 1 (derived from Table S4c of Jacob et al.). δX gives the increase in life expectancy for a settlement with the average population of 270.

Settlement (area number)	Remedial action	Costs (k€)	Averted dose (manSv)	δX (hours)	J-value
Elnoe (80)	RI	22.1	1.029	32.3	0.37
Vezhitsa (108)	RI	72.5	3.017	93.5	0.42
Drozdyn (103)	RI	29.3	1.205	34.8	0.46
Velikiy Cheremel (33)	RI	6.8	0.262	8.8	0.42
Vezhitsa (106)	RI	195.8	7.533	241.7	0.44
Velikiy Cheremel (34)	RI	6.8	0.253	7.8	0.48
Elnoe	MF	0.8	0.028	7.9	0.06
Staroe Selo (97)	RI	22.5	0.779	25.7	0.49
Elnoe (79)	RI	275.5	9.346	296.9	0.51
Klesov (128)	RI	15.8	0.513	16.4	0.53
Vezhitsa (105)	RI	145	4.569	142.4	0.56
Rudnya-Karpilovskaya (133)	RI	5	0.153	5.2	0.52
Staroe Selo (91)	RI	31.5	0.96	25.7	0.69
Drozdyn (104)	RI	14	0.414	14.3	0.55
Rudnya-Karpilovskaya (130)	RI	43.5	1.281	39	0.61

the productivity of the pasture land at the same time as reducing radioactivity uptake, and, moreover, this is likely to be an enduring effect. One might therefore expect to see RI and MF well represented in the choices constituting Strategy 1 and, indeed, each of these remedial actions attracts the highest possible value for degree-of-acceptability (see Table 1):

$$D_{A,RI} = D_{A,MF} = 1.0 \text{ for all } k \tag{5}$$

Proper quantification of such additional economic benefits would lead to a reduction in the effective cost of the decontamination countermeasure. Thus if the monetary benefit from improved agricultural productivity accounted for a quarter of the cost of the countermeasure, its J-value would be reduced to 75% of the figure it would otherwise have been. If this mechanism cancelled out two thirds of the cost, the J-value would be reduced to a third of its original value. The argument for implementation of the remedial measure would be strengthened in both cases. Unfortunately the necessary information on economic benefit has not been made available, so that we can comment only that the true J-value for cases where MF and RI are components of Strategy 1 will be lower than that quoted as a result of the additional benefits conferred.

3.4. *J-value results at the strategy level for remediation in Ukraine, Belarus and the Russian Federation*

Although the remedial measures were assumed by Jacob et al. to be implemented in 2010, the cost data provided in the paper relate to 2004, introducing a degree of anachronism. Our solution to this potential problem has been to assume that the countermeasure was put into force at its 2004 cost and to set the GDP per head, needed by the J-value method, at its 2004 value. Since some countermeasures, such as RI, can be effective over a period of 4–7 years (Table 2 of the Jacob study), we have assumed that dose is averted in a falling profile over the period 2004–2010, and have used the rate of increase of GDP per head attributable to that period in each of the three republics. Effectively we have simulated the period 2010–2016 by a time period 6 years earlier. Any discrepancy should not be major, however, since the increase in life expectancy, as used by the J-value method, is proportional to the dose averted, that is to say the difference between the dose received without the countermeasure and the dose received after it is adopted. Since the J-value operates on the dose difference, as provided by Jacob et al., it will not matter that the absolute value of the starting dose in 2010 will be different from the starting dose in 2004 as a result of radioactive decay.

Thomas and Waddington (2017) analysed the link between life expectancy and economic well-being as measured by GDP per head. The proposal under test was that decisions on spending to extend life made by people in all 180 countries of the world for which data were available were informed by the J-value at a J-value of 1.0. Allowance was made for a non-zero net discount rate to be applied to future human life to come, but it was found that the model's best match to the data occurred at a net discount rate of zero. As discussed in that paper, while a strictly positive net discount rate would have been possible, this would have required a countervailing increase in risk-aversion and hence an unnecessarily complex model to give the same answers. Having thus accounted satisfactorily for the pan-national differences in life expectancy observed with GDP per head, the J-value model has recently been further corroborated in a related but different application, namely predicting future life expectancy at birth within 35 industrialised countries (Thomas, 2017).

The zero value for net discount rate and the corroborated value for risk-aversion, namely 0.91, for use with the J-value in the UK may be used in Ramsey's formula to provide what is understood to be the first objective estimate of the pure time preference rate. This parameter was found to take the value 0.22% p.a. in the UK. This low figure is close to both to the estimate proposed by Ramsey himself (Ramsey, 1928), namely 0% p.a. and the figure, 0.1% p.a., suggested by Stern (2007, 2009). A further consequence of Ramsey's formula is that the social discount rate will be equal to the GDP growth rate per head. Averaged over 2004–2010, the growth rates in the three countries concerned were 8.2% per annum for Belarus, 4.6% p.a. for Russia and 3.1% for the Ukraine. Corresponding figures for GDP per head in 2004 were €7996 in Belarus, €10,906 in Russia and €5558 in Ukraine.

The mean change in life expectancy was computed using the CLEARE program (Change of Life Expectancy due to Atomic Radiation Exposure) based on the extended Marshall model (Marshall et al., 1983; Thomas et al., 2006b; Thomas and Jones, 2009). The CLEARE program is able to account for the life table characteristics (e.g. survival probabilities and life expectancies at different ages, for the two genders) for 180 nations of the 193 in the United Nations.

3.4.1. *Strategy 2*

Table 2 shows J-values for Strategy 2 when it is implemented by spending €1M in Belarus, €2M in Russia and €0.38M in Ukraine. Even though the life extension per person is small in all cases, less than a day, the J-value comes out at less than 1.0, thus providing justification for the expenditure. This is because the expenditure needed to achieve this increase in life expectancy is rather small: €43 on average.

3.4.2. *Strategy 1*

We may calculate an apparent J-value based on the first 3 numerical columns of Table 2. We know, of course, that the true J-value will lie below this figure, since part of the apparent cost ought to be cancelled out by the additional economic benefit that the countermeasure brings about, as explained in Section 3.3.

The apparent J-values of Strategy 1 are greater than those for Strategy 2 in all three republics. However they are still below 1.0, meaning that they could be recommended for implementation even without making proper allowance for the additional economic benefits provided.

Strategy 1 is not as effective, of course, at reducing the dose and hence extending life expectancy. The increase in life expectancy when the same gross amount is spent is 20% to 30% lower than for Strategy 2 in Belarus and Russia. While the average life extension for Ukraine under Strategy 1 is about twice that under Strategy 2, this benefit comes from a gross spend that is 3.6 times higher.

However, as noted, finding the true J-values for Strategy 1 would require an investigation of the additional economic benefits brought about by RI and MF.

The fact that the people interviewed in the rural areas were prepared to choose a Strategy 1 that was less effective than Strategy 2 in reducing radiation dose is understandable in view of the fact that the radiation dose in their areas 20 years after the accident was only slightly elevated above its natural background level of around 2 mSv y^{-1}. It will be remembered that a selection criterion for the application of these remediation measures was that the radiation dose received by the top 10% of worst affected individuals in the chosen settlements needed to be more than 1 mSv y^{-1} in 2004. The degree of harm that such additional radiation would cause is very small — a few days' or so loss of life expectancy. Given this very low level of hazard, it is hardly surprising that the interviewees were choosing economic advantage over a small radiological benefit.

Even so, all the J-value results as they stand confirm the view of Jacob et al. that remedial actions may be justified as cost-effective even when the dose has fallen to low levels. The advantage of the objective, J-value approach is that it dispenses with the subjective parameters, β and $D_{'Ar}$, $r = RA$, FA, ..., RS, that are needed in the Jacob methodology.

3.5. J-value results for individual agricultural and residential locations

As noted above, the Jacob study presented more detailed information for the costs and averted doses for the top fifteen remedial actions for individual locations in each of the three republics (Tables S4a–c and S5a–c in their supplementary data, with an extract of the findings given in Table 5 of Jacob et al.). The location-remediation pairs, (k, r), were ranked according to costs per unit dose averted for each strategy.

Jacob et al. do not provide population counts for each location, instead presenting the benefit of the countermeasure in terms of the collective dose averted, δH_C, for the N people affected. However this is sufficient for the calculation of a J-value as the linear relationship implicit in the ICRP risk coefficient (Thomas and Jones, 2009) causes the change in life expectancy, δX, to be proportional to the change in dose received by the average person, $\delta H = \delta H_C/N$. Hence $\delta X = a\delta H_C/N$ where a is a constant. But, by Eq. (3), the J-value works with the product, $N\delta X$, where $N\delta X = a\delta H_C$, and thus the J-value depends only on the collective dose averted. This proportionality will hold so long as the number of people affected, N, is large enough to produce an individual radiation dose, $\delta H = \delta H_C/N$, that is below 100 mSv in each year. For the purposes of illustration, the increase in life expectancy achieved is given in Tables 3–8 for the case where the number of people protected by the remedial action corresponds to the overall average settlement size of 270 people.

Taking the economic and actuarial data at their 2004 values allows the J-values to be calculated for each location/remedial action pair in Jacob et al. supplementary tables (Tables S5a–c and S4a–c). The results for Strategy 2 are presented in Tables 3–5 and those for Strategy 1 in Tables 6–8.

Even though the life extensions are small, of the order of hours or a few days, Tables 3–5 show that the J-values for the top 15 most cost-effective remedial measures under Strategy 2 are well below unity for all three republics. Hence these measures should certainly be recommended for implementation.

The ordering of the countermeasures derived from the J-value analysis is the same as that of Jacob et al. for Russia and Ukraine, and is roughly similar for Belarus.

A recommendation to implement may be made on the basis of the apparent J-values for Strategy 1, which takes into account of the additional economic benefits of the countermeasures, RI and MF, only through the degree-of-acceptability parameter, rather than by reducing the effective cost of the remedial action for dose reduction. Each of the apparent J-values is less than 1.0, although, at 0.97, that for Kholoch'e (73) in Belarus is getting close to that limiting value.

It is seen that ranking the actions by their J-value follows broadly the ranking of Jacob et al. for both Strategy 2 and Strategy 1. Note, however, that the J-value gives an objective measure of value for money, which the ranking of Jacob et al., with its reliance on subjective parameters, cannot provide. The trend suggests that the J-values of subsequent remediation actions (for which we do not have data) will be greater than those for the top fifteen measures reported here.

4. Urban decontamination

Moving away from agriculture, doses to the general population may be reduced through decontaminating people's living environment. This applies both in towns and in villages, but the short-hand term, "urban decontamination", is applied to both sizes of settlement here.

In the case of Chernobyl, although priority was generally given to agricultural countermeasures following the accident, nevertheless extensive decontamination of towns and settlements took place. In Russia, large scale decontamination activities came to an end in 1990, but urban decontamination was carried out until 2000 in Ukraine and Belarus. In Ukraine, approximately 100 settlements with doses above 1 mSv p.a. were targeted and Antsipov et al. (2000) reported that between 1991 and 1996, 30,280 m^2 of roofs were replaced, 87,500 m^3 of soil were removed, and 442,000 m^2 of land around buildings and houses were paved.

A wide range of decontamination activities are possible, and their costs and benefits depend on the local level of contamination, the degree of occupancy and the effectiveness of the technique employed. The UK Recovery Handbook for Nuclear Incidents (Nisbet et al., 2008) lists a large number of techniques, estimating costs and effectiveness for some. It is, however, difficult to obtain generalised data on the average costs, populations affected and reduction in doses achieved since many measures will be site specific.

In this Section, we consider three decontamination campaigns for which cost data and potential dose reductions are available, two relating to Chernobyl and one to Fukushima. It should be recognised that costs may be dependent on who carries out the work (for example, work by military personnel may less costly). Moreover, there will be a penalty associated with the radiation doses received by those carrying out the remediation work. Further costs will arise in the disposal of the radioactive material arising, and it is not known how much allowance has been made for this disposal in the figures cited below.

4.1. Dzerzhinsk kindergarten and school—Belarus

Antsipov et al. (2000) provide data on the decontamination of a kindergarten and school in the village of Dzerzhinsk, which lies in the Narovlya district of the Gomel region of Belarus. The decontamination work resulted in averted annual doses (D_a) of 0.2 mSv and 0.1 mSv for kindergarten and school children respectively. The number of children (N) attending the kindergarten each year was 30, and the same number were at the school. The cost of the decontamination measures was given as 14,000 € $manSv^{-1}$ in 1989.

Children in the former USSR customarily attend kindergarten for four years (ages 3–6) and then school for nine years (ages 7–15). A further two years at school (ages 16–17) is optional and not included in this calculation (stateuniversity.com, 2014; Educational System of Ukraine, 2014). We assume that the decontamination programme began in 1987, shortly after the accident, and continued until 2000 (Antsipov et al., 2000). The total dose averted over this 14-year period (T) is NTD_a, giving values of 0.084 manSv and 0.042 manSv for the kindergarten and school respectively (Table 9).

The mean change in life expectancy for the two populations was computed using the CLEARE program (Change of Life Expectancy due to Atomic Radiation Exposure). The life tables applicable to the USSR in 1990 were used and a steady-state population assumed (e.g. for every child who leaves the school at age 16, another one starts at age 7). The kindergarten and school populations were treated as independent for simplicity. The increase in mean life expectancy due to the reduction

Table 9 – Decontamination of a kindergarten and school.

	Population	Collective dose averted (man-Sv)	Annual averted dose per person (mSv)	Increase in life expectancy (hours)	Cost (euros)	J-value
Kindergarten	30	0.084	0.2	6.0	1176	0.65
School	30	0.042	0.1	5.4	588	0.35

Table 10 – Urban decontamination in the Bryansk oblast of Russia. The costs are given on the basis that the decontamination work benefitted the whole population uniformly.

	Population	Collective dose averted (man-Sv)	Mean lifetime dose averted per person (mSv)	Increase in life expectancy (days)	Cost (roubles)	J-value
Novozybkov	46,000	160	3.5	0.7	3,067,000	0.61
39 villages	14,000	800	57.1	10.9	933,000	0.037
53 other areas	30,000	400	13.3	2.5	2,000,000	0.16
Total	90,000	1360	15.1	2.9	6,000,000	0.14

in radiation dose was calculated to be 6.0 h per child in the kindergarten and 5.4 h per child in the school based on ICRP coefficients (Thomas and Jones, 2009).

The average GDP per head[2] of the three republics in 1990 was €9314. The net discount rate was set at 0, in line with Thomas and Waddington (2017), making the social discount rate equal to the average growth rate of 0.89% y^{-1}. The cost of the decontamination measures was €1176 for the kindergarten and €588 for the school (based on the cost per manSv from Antsipov et al. and the total averted doses).

These give J-values for the decontamination measures of J = 0.65 for the kindergarten and J = 0.35 for the school (Table 9). The fact that both these J-values are below 1.0 provides justification for the decontamination measures.

4.2. *Bryansk oblast—Russia*

Balonov et al. (1992) discussed a programme of large-scale decontamination of populated areas in the Bryansk oblast of the Russian Republic. In 1989, a clean-up campaign was initiated in 93 populated areas, consisting of the town of Novozybkov (population 46,000), 39 villages with a combined population of 14,000 and 53 other areas with a population of 30,000. The programme reduced mean doses by 25% ± 5%, with the collective dose over all areas being reduced by 1360 manSv (Table 10).

The mean dose averted for each person in each of the three populations is given in Table 10, ranging from 3 to 57 mSv over his/her lifetime. We assume that this dose would have been received over a period of 70 years (approximately the life expectancy at birth) and that the annual dose decreases according to the external radioactive decay profile given by the Moscow Institute of Biophysics (MIB) model (Lochard and Schneider, 1992). The CLEARE software was used to calculate the gain in life expectancy due to averting these doses. The results (Table 10) indicate that the decontamination programme extended the life expectancies of the three groups by 16 h in Novozybkov, 11 days in the villages and 3 days in the other populated areas. [An alternative interpretation of lifetime dose was also programmed, namely that the dose was received over the average life expectancy, 37 years, of those living at the time of the accident; this produced very similar figures for the extension of life expectancy.]

The economic data against which we evaluated the cost-effectiveness of the clean-up programme were taken from Waddington et al. (2017a, their table* 1). The GDP per capita of the USSR in 1990 was 3532 roubles. The net discount rate was set at 0 (Thomas and Waddington, 2017) and so the social discount rate was equal to the growth rate of 0.94% per annum.

The cost of employing the workforce was given by Balanov et al. as 6 M roubles (1989 prices). Assuming that the total cost was uniformly distributed across the combined population of 90,000 people, this gives a mean cost of 67 roubles per person. On this basis, the cost-effectiveness of the decontamination programme varies with population group (Table 10) giving J-values of 0.61 for Novozybkov, 0.16 for the other populated areas and 0.037 for the villages.

It is seen that the clean-up was justified for all these cases, particularly in the 39 villages of Bryansk. It may be, however, that economies of scale are at work here, with the geographically dispersed nature of the villages making their decontamination more expensive per head than for the urban areas. If this were true, it would tend to lower the J-values for the towns and increase the J-value for the rural areas.

4.3. *Fukushima City—Japan*

The cost of decontaminating 110,000 houses in Fukushima City (65 km from the plant) was reported as $370M (World Nuclear News, 2012). The aim was to reduce the dose to the 290,000 inhabitants from 5–10 mSv y^{-1} to 1 mSv y^{-1}. The clean-up of the first 4000 houses reduced dose rates from 7 mSv y^{-1} to 2 mSv y^{-1} and a further reduction to 1 mSv y^{-1} was projected to come from cleaning roads and gutters. We have used the reported figures to assess the potential benefit of a possible urban decontamination exercise. It was assumed that there would be a reduction of 6 mSv in the first year, with further doses averted in future years as a result of much of the radioactive contaminant being removed.

Assuming the dominant decay processes were similar to those in force at Chernobyl, the MIB model predicted that the radiation dose would fall to about a tenth of the natural background level after 70 years. This dose profile was fed into the CLEARE program, which suggested that the saving in life expectancy for the inhabitants of Fukushima City would have been 15 days. Applying a net discount rate of 0%, a social

[2] The World Bank (2012) gives the population-averaged GDP per capita of Belarus, Russia and Ukraine as $7334 (international dollars) in 1990 (see Waddington et al., 2017a). We have used a market exchange rate (Newbold et al., 1998; FXTOP, 2014) of 1.27 European Currency Units (equivalent to the euro at its introduction in 1999) to the US dollar (equivalent to the international dollar by definition), to estimate the GDP in euros.

discount rate of 0.6% and $34,294 as the GDP per head, the J-value turns out to be 0.09. This suggests that the clean up at Fukushima City would be highly cost-effective. The very low J-value figure implies that the conclusion is robust against reporting errors.

5. Conclusions

The J-value has been applied to evaluate the cost-effectiveness of a number of agricultural countermeasures proposed for affected areas of Belarus, Ukraine and Russia 20 years after the Chernobyl accident. The measures are shown to be worthwhile, despite being scheduled for implementation a long time after the accident in locations where the radiation level had already decayed to close to background levels. The results confirm the conclusions of Jacob et al. (2009) and extend them by providing not only a ranking but an objective quantification of the degree of economic effectiveness of each countermeasure.

While the higher cost per man-Sievert averted under Strategy 1 as compared with Strategy 2 is explained in the Jacob study by the subjective parameter, degree-of-acceptability, it would appear that the predominant motivation behind the difference was the higher economic payback, hardly surprisingly given the already low level of radiation. Estimating the extent of this additional economic benefit would allow the true J-values to be found for Strategy 1, which would be expected to be closer to or below those generated under Strategy 2.

Two cases of urban decontamination in the wake of the Chernobyl accident were examined using the J-value, one in Belarus and one in Russia, together with a third urban decontamination exercise in Fukushima City. The J-value showed that these applications of decontamination were all justified.

Remediation measures can be applied to both agricultural and urban environments affected by radioactive fallout following a major nuclear reactor accident. It is clear that a range of remedial actions can produce useful and cost-effective reductions in the dose levels experienced by those living in areas subject to some degree of continuing radiation exposure. The J-value method provides a rigorous means of identifying and prioritising these.

As a broader point, while the measures discussed in the paper were all remediations against radioactive fallout, the generality of the J-value method means that it could be used to assess objectively the degree of desirability of other interventions to improve health and extend life in these or other populations.

Acknowledgements

This work was carried out as part of the NREFS project, Management of Nuclear Risk Issues: Environmental, Financial and Safety, led by City, University of London and carried out in collaboration with Manchester, Warwick and Open Universities and with the support of the Atomic Energy Commission of India as part of the UK-India Civil Nuclear Power Collaboration. The authors acknowledge gratefully the support of the Engineering and Physical Sciences Research Council (EPSRC) under grant reference number EP/K007580/1. The views expressed in the paper are those of the authors and not necessarily those of the NREFS project.

The data used in the paper have been listed in the tables and text.

Professor Thomas was Principal Investigator throughout the NREFS project (1.12.2012–30.11.2014) during his time at City, University of London, Ross Technologies, Professor Taylor and Mr Vaughan provided services under contract to City University during the NREFS project.

Professor Thomas's contribution to the paper was written mainly since he has been with the Safety Systems Research Centre in the Queen's School of Engineering at the University of Bristol and he is grateful to that University for its sponsorship of open access publication in fulfilment of EPSRC's wishes.

Appendix A. Exposition of the method used in the Jacob study

A.1 Strategy 2

Strategy 2 is the more basic of the two strategies considered, and so will be introduced first.

Let k be the location, which may be an agricultural production area or a residential neighbourhood containing a cohort of 10 people. Let r be the remedial action, which will be one of {RA, FA, FP, MF, IM, RS}.

This notation is a simplification of that used by Jacob et al., who employed the double subscript, ij, rather than a single subscript, k. In Jacob et al. (2009), j denotes an agricultural area while i identifies a residential cohort of 10 people. However, the ordering under the two indicators, i and j, may be made sequential without loss of generality:

$$1, 2, \ldots, j, \ldots, n_j, n_j+1, n_j+2, \ldots, n_j+i, \ldots, n_j+n_i \tag{A.1}$$

where n_j is the number of agricultural areas and n_i is the number of settlement cohorts. Thus the ordering, (A.1), may be replaced by a single ordering under the index, k:

$$1, 2, \ldots, k, \ldots, n_k \tag{A.2}$$

where $n_k = n_j + n_i$. Ordering (A.2) can be seen to have a one-to-one correspondence with ordering (A.1).

The Jacob algorithm then seeks to find the remedial action, r, and the location, k, that maximise the objective function:

$$\frac{\min_{k,r} C_{Dkr}}{C_{Dkr}} \text{ over all } k \text{ and } r \tag{A.3}$$

where C_{Dkr} is the cost of averting a man-Sievert (€ Sv^{-1}) at location k under remedial action, r.

Objective function (A.3) has the property, for any given k and r, that if $C_{Dkr} > \min_{k,r} C_{Dkr}$, then $\min_{k,r} C_{Dkr}/C_{Dkr} < 1$. On the other hand, if $C_{Dkr} = \min_{k,r} C_{Dkr}$, then $\min_{k,r} C_{Dkr}/C_{Dkr} = 1$. And it is obviously not possible for C_{Dkr} to be less than $\min_{k,r} C_{Dkr}$. Hence

$$\max_{k,r}\left\{\frac{\min_{k,r} C_{Dkr}}{C_{Dkr}}\right\} = 1 \tag{A.4}$$

Since all remediation costs must be positive, it follows that:

$$0 < \frac{\min_{k,r} C_{Dkr}}{C_{Dkr}} \leq 1 \quad \text{over all } k \text{ and } r \tag{A.5}$$

A possibly more obvious way of proceeding would be to normalise the cost per dose averted, C_{Dkr}, by dividing by $\min_{k,r} C_{Dkr}$. The objective function, $C_{Dkr}/\min_{k,r} C_{Dkr}$, is the inverse of objective function (A.3) and would thus need to be minimised. The two methods are equivalent, but the route adopted by Jacob et al. has the advantage of scaling the objective function so that it will always lie between 0 and 1.

Once the most cost-effective pairing of location and remedial action, $(k = k_1, r = r_1)$, has been found, location k_1 may be removed from consideration and the process repeated for the remaining $(n_k - 1)$ locations. This process is continued until there are no more locations left, producing a priority ordering, (k_1, r_1), (k_2, r_2), (k_3, r_3), $\ldots$, $\left(k_{n_k}, r_{n_k}\right)$.

It is understood that each location is assumed to be served with only one remediation measure:

> “Averted doses and costs of remedial actions, which have to be performed subsequently, are not considered in our calculations.” (Jacob et al., 2009)

Jacob et al. (2009) assume a fixed budget for remediation so that remedial actions should be undertaken in the sequential order of priority until all the money has been used up. They call the resulting remedial spending decisions “Strategy 2”.

For Strategy 2, Jacob et al. considered a range of possible remediation budgets for each republic. A budget in a given sum for a republic was described by Jacob et al. as “arbitrarily chosen funds”.

A.2 Strategy 1

Jacob et al. now introduce a further parameter, the degree-of-acceptability, D_A. This is a subjective parameter to which they ascribed a value after interviewing inhabitants of local settlements and local stake-holders in the most contaminated regions of the three affected countries, Belarus, Ukraine and the Russian Federation. Degree-of-acceptability for a remedial action was found to be independent of both country and settlement.

Objective function (A.3) was augmented in the Jacob study to take account of the new parameter. The values of r and k are now sought that maximise the expanded objective function:

$$\beta \frac{\min_{k,r} C_{Dkr}}{C_{Dkr}} + (1-\beta)\, D_{Ar} \text{ over all } k \text{ and } r \qquad \text{(A.6)}$$

where D_{Ar} is the degree-of-acceptability for remediation action, r, and β is a further subjective parameter set by the user: $0 \le \beta \le 1$.

As with the previous algorithm, once the most cost-effective pairing, $(k = k_1, r = r_1)$, has been found, location, k_1, is removed from consideration and the process is repeated for the remaining $(n_k - 1)$ locations. This process of sequential elimination of the best remaining location is continued until there are no more locations left, producing a priority ordering, (k_1, r_1), (k_2, r_2), (k_3, r_3), $\ldots$, $\left(k_{n_k}, r_{n_k}\right)$.

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